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# Self-Propelled In-Tube Shuttle and Control System for Automated Measurements of Magnetic Field Alignment*

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# SELF-PROPELLED IN-TUBE SHUTTLE AND CONTROL SYSTEM FOR AUTOMATED MEASUREMENTS OF MAGNETIC FIELD ALIGNMENT

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## ABSTRACT

A magnetic field alignment gauge is used to measure the field angle as a function of axial position in each of the magnets for the Superconducting Super Collider (SSC). Present measurements are made by manually pushing the gauge through the magnet bore tube and stopping at intervals to record field measurements. Gauge location is controlled through graduation marks and alignment pins on the push rods. Field measurements are recorded on a logging multimeter with tape output. Described is a computerized control system being developed to replace the manual procedure for field alignment measurements. The automated system employs a pneumatic walking device to move the measurement gauge through the bore tube. Movement of the device, called the Self-Propelled In-Tube Shuttle (SPITS), is accomplished through an integral, gas driven, double-acting cylinder. The motion of the SPITS is transferred to the bore tube by means of a pair of controlled, retractable support feet. Control of the SPITS is accomplished through an RS-422 interface from an IBM-compatible computer to a series of solenoid-actuated air valves. Direction of SPITS travel is determined by the air-valve sequence, and is managed through the control software. Precise axial position of the gauge within the magnet is returned to the control system through an optically-encoded digital position transducer attached to the shuttle. Discussed is the performance of the transport device and control system during preliminary testing of the first prototype shuttle.

## INTRODUCTION

An electrical gauge to measure magnetic field angle has been developed at Fermilab[1]. The gauge is used to measure the field angle as a function of axial position along the length of SSC cold iron superconducting magnets. At present, measurements are made by inserting the gauge into a magnet beam tube and pushing it through the length of the bore with long aluminum rods. Measurements of the field direction are made and recorded at 7.62 cm. intervals. This method is

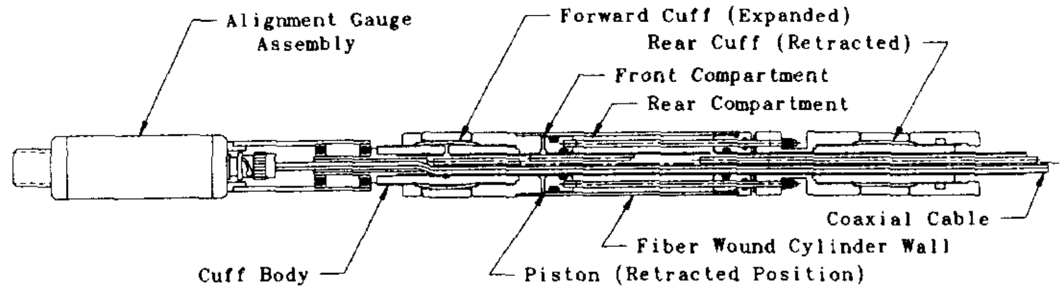


Figure 1. Self Propelled In-Tube Shuttle (SPITS).

slow and labor-intensive; therefore, a development program was initiated to automate the measurements. The result has been a unique integration of mechanics and software that will permit the automated acquisition of magnetic field data at precise locations inside the 4 cm. bore of an SSC dipole magnet beam tube.

## SELF-PROPELLED IN-TUBE SHUTTLE

Integral to the automated system is a transport device called the Self-Propelled In-Tube Shuttle (SPITS). The device is shown in Figure 1. The SPITS is capable of pushing or pulling the field alignment gauge through the magnet bore tube. The alignment gauge assembly is attached to the SPITS through a threaded connection. This connection will allow other measurement devices to be readily adaptable to the SPITS. The transport device is constructed entirely of non-magnetic materials which do not interfere with the magnetic field measurements of the alignment gauge.

Internal to the transport is a pneumatic piston which controls the length of the stroke. The prototype SPITS assembly has a maximum stroke of 7.62 cm. Separate compartments on each side of the piston control the direction of transport travel. Four internal ports with pneumatic passages connect the piston compartments and inflatable cuffs to the supply gas. The present SPITS design can accommodate gas pressures to 620 kPa.

The transport device contains two independent inflatable cuffs. One cuff assembly is mounted near the front of the device; the second at the rear. Figure 2 illustrates a prototype cuff assembly and is representative of the assemblies within the SPITS device. The neoprene membrane of each cuff is bonded to three glass-epoxy composite pieces separated at 120° angles. The composite pieces are contoured to fit the inner diameter of the beam tube, and contact the beam tube when the membrane is pressurized.

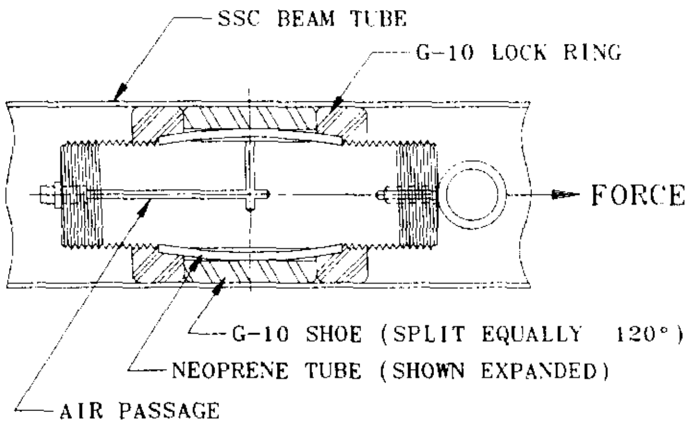


Figure 2. Prototype cuff assembly.

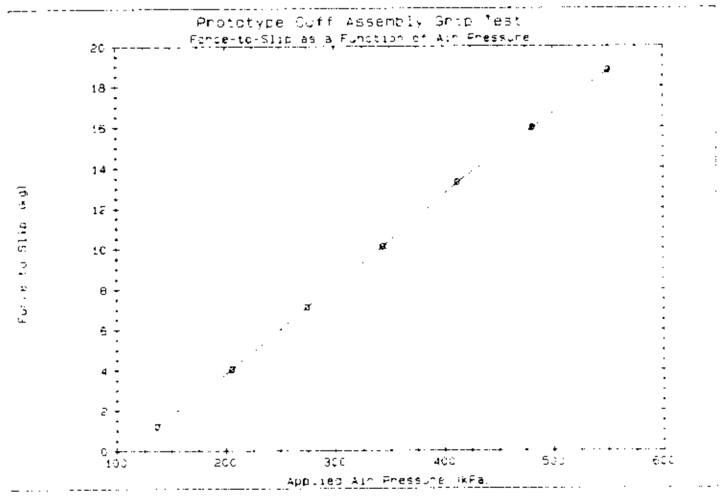


Figure 3. Force-to-slip verses cuff air pressure.

Tests were conducted on the prototype cuff assembly to determine the holding power of the cuff design. A commercial tensile-testing machine was used to apply an axial force in the direction shown in Figure 2. Data was taken with the cuff pressurized to several pressures between 138 kPa and 552 kPa. The force which caused the assembly to slip was measured for each pressure with the force-to-slip measurement repeated three times. Figure 3 shows the average force-to-slip as a function of internal air pressure.

## SPITS CONTROL SYSTEM

The supply gas used to control the movement of the transport device is routed to the device through a series of four miniature solenoid-controlled air valves. Each valve uses two solenoids which control the flow of the inlet and exhaust gas, respectively, and provide substantial control over the pressurization and exhaust timing of each component. Needle valves throttle the gas flow through each exhaust port, and provide smooth forward and reverse movement of the transport. Fluid movement of the transport through the magnet bore tube is critical given the sensitive nature of the field alignment gauge.

The solenoids are energized through a series of solid state relays. The relays are part of a modular programmable controller system connected through a RS-422 serial interface to an IBM-compatible host computer. The control system is shown in block diagram in Figure 4. Software was

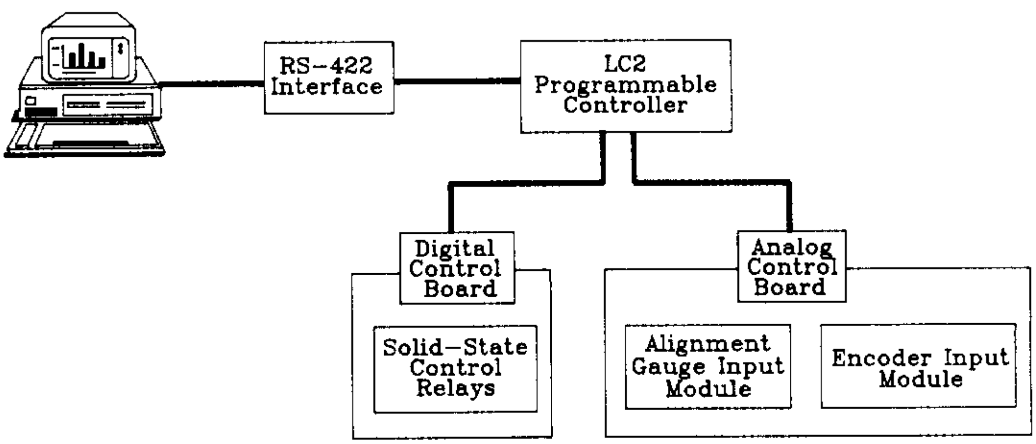


Figure 4. Block diagram of the SPITS computerized control system.

developed to control the timing sequence that produces forward and reverse movement. When fully implemented, the control portion of the software will be downloaded to the local controller. The local controller will then process the entire control sequence upon a single command from the host computer. This capability frees the host computer to perform data manipulation between measurement points.

The control sequence for one stroke of forward travel is outlined in Table 1. Reverse travel is accomplished by reversing the order of the control sequence. Figure 1 should be used to reference transport components.

Table 1. Control sequence to advance the SPITS transport.

| STEP | ACTION | RESULT |
|---|---|---|
| 1 | Pressurize rear cuff | Rear cuff expands to contact the beam tube, prohibiting backward movement. |
| 2 | Exhaust front cuff | Front cuff retracts from the beam tube wall. |
| 3 | Pressurize front compartment | Pressurized gas enters the compartment before the piston, which should cause the transport to extend axially. However, because the exhaust valve controlling the compartment behind the piston is closed, the device cannot move. |
| 4 | Exhaust rear compartment | The exhaust valve on the rear piston compartment opens, allowing the gas to escape. As the gas escapes from the rear compartment, gas is allowed to enter the front compartment, causing the transport to extend axially. The exhaust gas passes through a needle valve that is throttled to slow the rate of exhaust. The result is a gentle expansion of the transport device. |
| 5 | Pressurize front cuff | Front cuff expands and contacts the beam tube, stopping forward movement. |
| 6 | Exhaust rear cuff | Rear cuff retracts, releasing the grip on the beam tube. |
| 7 | Pressurize rear compartment | Pressurized gas enters the rear compartment, which should cause the transport to contract axially. However, pressure still exists in the front compartment, so the device is held stationary. |
| 8 | Exhaust front compartment | The exhaust valve on the front compartment opens, allowing the gas to escape. As the gas escapes from the front compartment, gas is allowed to enter the rear compartment, causing the transport to contract axially. As the device is held against the beam tube by the front cuff, the rear of the device is brought forward. Again, the rate of exhaust is throttled to provide gentle movement of the device. |

By design, one sequence of events moves the transport a distance of approximately 7.62 cm. An optically-encoded digital position transducer is used to maintain exact positioning. Location of the transport is determined by attaching the cable from the transducer to the rear of the transport. As the transport moves through the beam tube, the cable rotates a spring loaded shaft coupled to a rotary digital encoder. Digital pulses from the transducer at the rate of 246 per cm. of transport travel are output to the control computer. The operation of the positioning system is still under development. The objective is to have the computer determine, by means of a feedback loop, when a desired location has been reached. A command will then be sent to the solenoid valves to pressurize the foremost cuff. The rapid pressurization will stop the transport at the desired position. With the front cuff pressurized, the remaining valve sequence will be completed to ready the transport for the next stroke. Some adjustment of the pressurization timing will be necessary during start-up to achieve the desired degree of positioning accuracy.

## INSTRUMENTATION CABLE / AIR LINE SUPPLY SYSTEM

A compact utility system has been designed to manage the air lines and instrumentation cables for the SPITS as the device moves along the 16.3 meter long beam tube. The take-up system is shown in Figure 5. The compact system will fit on top of a 60.5 cm. by 91 cm. tool and die table, providing elevation control and system portability.

Constant tension must be maintained on the supply lines during the entire range of SPITS travel. Tension is maintained by connecting the output reel to a constant-speed gear motor through an adjustable particle clutch, set at 0.68 kg of tension. A series of reels with different diameters achieves a step-down ratio of 125:1 so that the connecting end of the supply lines moves less than 14 cm. throughout the entire 16.3 meters of SPITS travel. Air lines and electronic cables from the control system are easily connected to the main supply lines through this interface. Winding guides will be used to lay the cables and hoses down on the reel with uniform spacing.

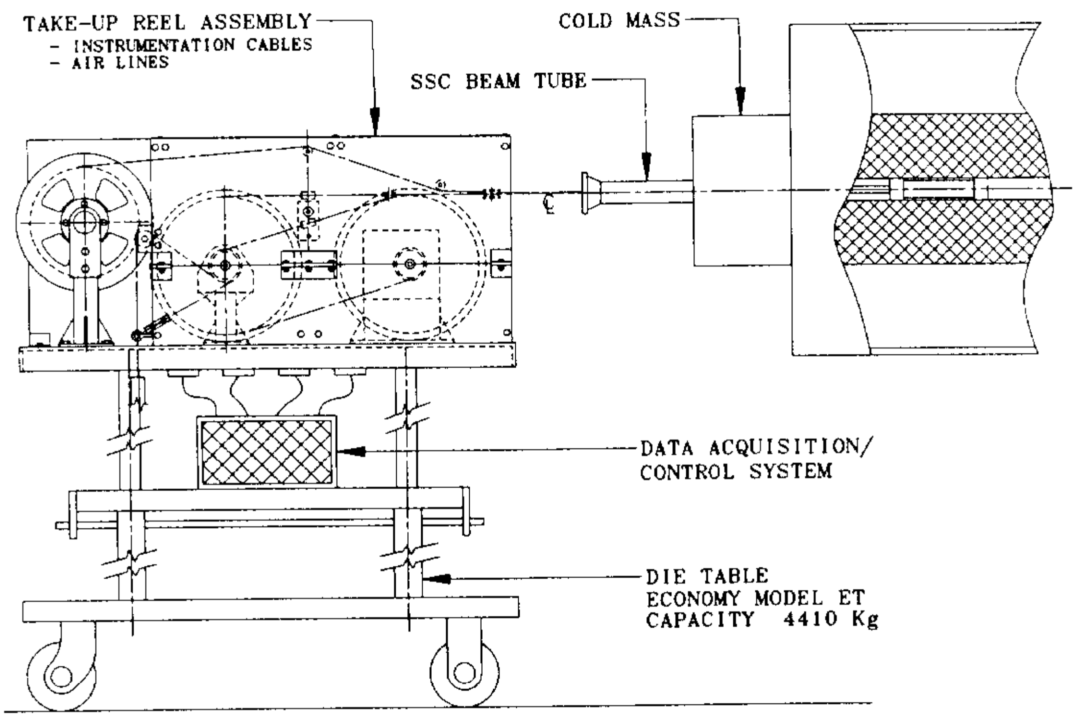


Figure 5. Air line / electronic cable take-up system.

The first prototype SPITS device was cycled along a 1.3 meter section of SSC beam tube to measure transport performance over time. The test program called for the device to travel the equivalent of 50 SSC beam tube lengths; the actual distance travelled during testing was 838 linear meters. Fiducials placed on the body of the transport were used to measure axial and rotational creep during travel.

For these measurements, axial creep is defined as the actual change in axial displacement of the device over time. By design, there should be zero displacement due to axial creep; the device should return to its starting location. Displacement was measured as the change in axial position of a circumferential alignment mark with reference to the beam tube end from beginning to end of each run, and was recorded in cm. per meter of travel. Rotational creep is defined as the amount of azimuthal shift of the transport during travel, and was measured by the angular change in axial alignment marks from beginning to end of each run. Rotational creep was recorded in degrees per meter of travel. All measurements were made using a flexible machinist's scale with a resolution of 0.5 mm.

Measurements were taken over a 7-day period in which 11 separate measurement runs were conducted. The transport device was re-aligned with the fiducials before each run. The average time required to travel one beam tube length was 56 minutes. This is a significant reduction in time compared to that presently required to move the alignment gauge through a beam tube. Furthermore, the speed of the transport is programmable through the control software, and can be optimized to meet specific measurement needs.

Figure 6 presents the amount of rotational creep measured for each run. A slight downward trend in the amount of rotation can be seen as the test proceeded. The maximum amount of rotation for a single run was 0.82 degrees per meter of travel. Given this degree of change, the total rotation over a beam tube length of 16.3 meters would be 13.37 degrees. This is unacceptable as the maximum amount of rotation tolerable for the field alignment gauge is +/- 5 degrees. Development of a gauge-to-transport connection that will allow free rotation of the gauge with respect to the transport is under consideration. Possible solutions include frictionless mechanical bearings or spherical air bearings. Adding ballast weight at the gauge bottom with non-magnetic shims would then maintain stability of the gauge during transport travel.

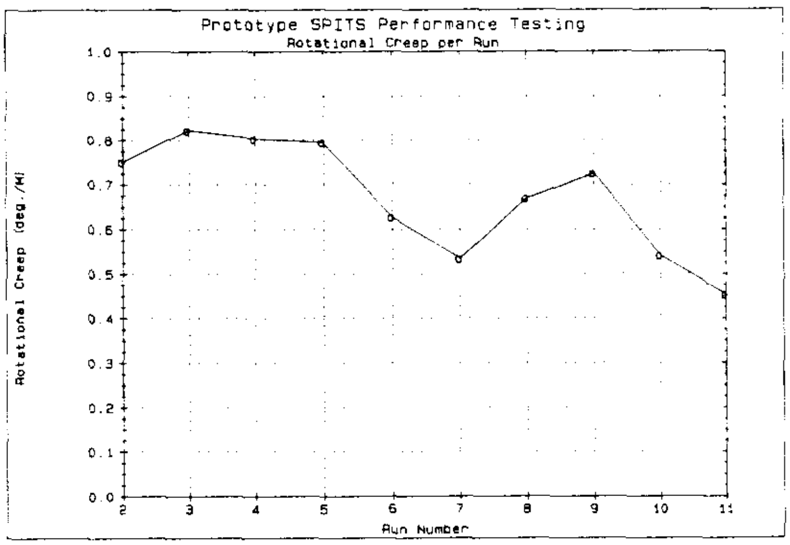


Figure 6. Rotational creep of the transport device during testing.

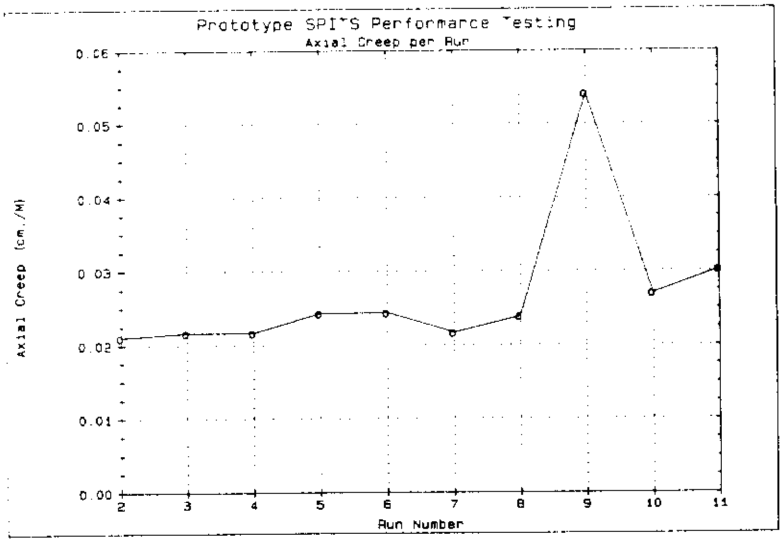


Figure 7. Axial creep of the transport device during testing.

Figure 7 presents the results of the axial creep measurements. The large amount of creep in run 9 is most likely caused by measurement error, and should be disregarded. The degree of transport creep in the remaining data points is relatively constant, although a slight upward trend is observed near the end of the testing. As final positioning of the transport will be accomplished through a digitally-encoded positioning feedback loop, the small amount of creep measured is not of concern.

## SUMMARY

A transport device for automated magnetic field measurements has been designed and tested. At present, the device is also being considered for use as a laser target transport for magnet alignment measurements. Axial location of the SPITS is achievable through the use of a digital positioning transducer. Preliminary test results indicate a problem with angular rotation; however, several methods to resolve this problem are being considered. The transport system is still under development. Results of initial tests warrant continued R&D to address the shortcomings of the system. Early data indicate that the transport will significantly reduce the time required to make field angle measurements. The transport system can be operated by one person.

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## REFERENCES

1. M. Kuchnir and Ed. E. Schmidt, IEEE Trans. Magn. 24, 950 (1988).